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Simulated and Experimental In-Wall Temperatures for 120-mm Ammunition

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13. ABSTRACT *(Maximum 200 words)*

Bore and chamber surface, as well as subsurface, temperature predictions are made for the U. S. Army M256 120-mm cannon firing M865, M829, and DM13 cartridges. The surface temperature predictions are validated by comparison with other numerical modeling results, while the subsurface temperature predictions are compared directly with experimental measurements made by in-wall thermocouples.

The surface temperature predictions fall in line with other numerical estimates, and, in general, the simulated probe temperatures at each axial location are within the circumferential and round-to-round variation in the experimental probe temperatures.

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1. INTRODUCTION

M865 and M829 cartridges were fired in a gun tube instrumented by personnel from the U.S. Army Combat Systems Test Activity (CSTA) using Veritay Technology, Inc., in-wall thermocouple (IWTC) probes. The probes were installed at each of three circumferential positions (starting at the top and spaced 120° apart) at each of four axial locations along the gun tube. Prior to firing, the M865 rounds were conditioned at 21° C and the M829 rounds were conditioned at 21° C and 49° C. These tests were conducted in October 1993. Figure 1 displays a representation of an installed Veritay IWTC. Figure 2 displays a drawing of the instrumented gun tube.

In August 1994, a second gun tube was instrumented with "welded" thermocouples, and a preliminary DM13 round conditioned at about 21° C was fired; this round served as a warmer round as well as a preliminary IWTC instrumentation checkout round. Due to unexpected data acquisition problems for this DM13 round, only one data channel was recorded, corresponding to an IWTC probe location at 457 mm from the rear face of the tube (RFT). Figure 3 displays a representation of the welded IWTC. Figure 4 displays a drawing of the instrumented gun tube. It is noted that the 457-mm (18-in) probe location for this DM13 round actually corresponds to the chamber surface, not the bore surface.

All simulations are derived from XKTC (Gough 1990) and XBR2D-V29* (Crickenberger, Talley, and Talley 1994) finite difference calculations. The thermal output of this calculation method has been successfully demonstrated in past simulation studies (e.g., Conroy [1991] and Keller et al. [1993]).

In this study, we chose as input for the XBR2D-V29 code, the following thermal and mechanical properties for the barrel:

- chrome thickness: 0.14 mm (0.0055 in)
- chrome thermal conductivity: 84 J/(m-s-K) (10.5 lbf/s-R)
- chrome thermal diffusivity: 2.3E-05 m^2/s (0.036 in^2/s)
- steel thermal conductivity: 38 J/(m-s-K) (4.8 lbf/s-R)
- steel thermal diffusivity: 1.0E-05 m^2/s (0.016 in^2/s)

* This version of XBR2D-V29 code is based on the program originated by Veritay Technology, Inc., and now incorporates revisions introduced by the U.S. Army Research Laboratory.

2. SIMULATED BORE SURFACE TEMPERATURES

Figure 5 displays four plots of the simulated bore surface temperatures for the M865 (21° C), M829 (21° C and 49° C), and DM13 (21° C) cartridges. Whereas, the M865 and M829 plots show curves for four axial locations along the gun tube, the DM13 plot displays only a single location—and this location corresponds to the chamber instead of the bore.

It is observed from these plots that bore surface temperatures generally decrease with increasing distance from the chamber. However, in the case of the M865 and M829 rounds at 21° C, the 1,350-mm (53.1-in) curve is shown to be slightly higher than the 1,050-mm (41.3-in) curve. Such an anomaly is not exhibited by the M829 plot for 49° C, and it may be that this peculiarity at 21° C is an indication that the spatial and/or temporal grid size in the XKTC and/or the XBR2D-V29 program is not small enough.

From Figure 5, the predicted peak bore surface temperatures, after firing an M829 at 21° C, are about 1,405 K and 1,225 K at 640 mm and 1,350 mm from the RFT, respectively. A similar calculation was done by Bundy, Gerber, and Bradley (1993) for the same ammunition and initial conditions, but a different chrome thickness, using a different numerical treatment. For a chrome thickness set at 0.10 mm, they predicted peak bore surface temperatures of about 1,650 K and 1,425 K, at 700 mm and 1,400 mm from the RFT, respectively. With the chrome thickness set at 0.16 mm, they predicted about 1,200 K and 1,050 K, respectively. Thus, the predictions of Figure 5, which are based on a chrome layer of 0.14 mm, are in close proximity to the Bundy, Gerber, and Bradley calculations (1993).

We note that in no case is the predicted bore surface temperature high enough to melt the chrome layer (having a melting temperature near 2,130 K). This is consistent with the fact that even though chrome can be found missing in M256 gun barrels, there has never been any indication that it is missing due to melting, rather, it appears to chip off.

We can also comment that the predicted bore surface temperature is lowest for the M865 at 21° C and highest for the M829 at 49° C; we will show this is borne out by experimental data as well.

3. EXPERIMENTAL IWTC PROBE TEMPERATURES

Figure 6 displays individual plots of experimental probe measurements at 21° C for each of two different cartridge types (M829 and DM13). In the case of the M829 cartridge type, plots for three different test rounds are displayed, i.e., for "round no. 2," "round no. 6," and "round no. 10." (Other round numbers corresponded to different ammunition.)

Each curve within each plot is designated by its round number together with its circumferential position, in degrees. For example, "no. 2/120" represents round no. 2 for the probe positioned at 120° from the top of the gun tube in the clockwise direction, looking from the breech to the muzzle.

For the M829 rounds, obvious discrepancies between the curves are evident (i.e., they do not overlay each other). The three circumferential probe temperatures are estimated to vary by as much as 25% from the visual appraisal of their (pooled) mean profile. In addition to the difference in magnitude, the initial rise rate of the 0° probe is distinctly different than the 120° and 240° probes. Furthermore, the ordering of the discrepancies in the circumferential probe temperatures is the same for all three M829 rounds (i.e., 120° > 240° > 0°). Several reasons for such discrepancy may be speculated and these include:

- nonuniform thickness of metal (steel and chrome) between the bore surface and the probe tip
- variation in contact resistance between the steel and chrome interfaces (e.g., partial chrome delamination)
- nonuniform contact between IWTC probe tip and metal substrate (e.g., oil/dirt contamination, etc.)
- nonuniform circumferential heat input

The variation in contact resistance at the chrome-steel interface, second bullet above, could come about by partial chrome delamination. Figure 7 illustrates, from a different barrel, how the chrome can partially separate from the steel, with the void filled by nonthermally conducting material.

Most likely, the first reason above is the largest contributor to the discrepancy in circumferential probe temperatures. In subsequent plots we will show that a variation in the metal thickness between the probe tip and the bore surface of from 0.25 to 0.50 mm (0.01 to 0.02 in) would account for the circumferential temperature inconsistency. In this regard, we had anticipated an error in the IWTC depth, due to an

uncertainty in the barrel wall thickness at the location where each probe hole was drilled, of from 0.1 to 0.3 mm.

Lastly, Figure 6 shows that the probe temperatures at the same axial and circumferential location can vary by as much as 20% from one round to the next.

We are unable to display a complete set of circumferential probe measurements at each axial location, nor give, with confidence, the circumferentially averaged probe temperature at each axial location, due to improper functioning of one or more IWTC probes at each axial location, except 640 mm (as shown in Figure 6). Nevertheless, we will present at least one experimental probe temperature at every axial location in the comparison of theory with experiment, discussed next.

A single plot for the DM13 round is included within Figure 6 to compare with the M829 round. On the one hand, the M829 is ballistically similar to the DM13 round, which would lead one to expect a similar response from the two rounds. On the other hand, the plots are expected to differ from the standpoints of probe location and probe type (i.e., locations at 640 mm vs. 457 mm [25.2 in vs. 18 in], and Veritay vs. welded IWTC probe types, respectively). Additional discussion of the DM13 probe response is pursued in a following section.

4. SIMULATED vs. EXPERIMENTAL IWTC PROBE TEMPERATURES

Simulated IWTC probe performance for four different rounds are discussed in this section (see Table 1).

In the case of the DM13 round, only a single probe location at 457 mm (18 in) from RFT is reported. As previously discussed, this location actually corresponds to the forward part of the gun chamber. The nominal probe depth at this location is assumed to be 1.52 mm (0.06 in).**

For the M865 and M829 rounds, to be described, probe temperatures correspond to axial locations of 640, 1,050, 1,350, and 1,600 mm (25.2, 41.3, 53.1, and 63.0 in) from RFT. For each of these plots, the probe depth is taken to be 1.27 mm (0.05 in).

** As mentioned previously, there is an uncertainty in the drilled probe hole depth of 0.1 to 0.3 mm.

Table 1. Experimental-Numerical Test Matrix

Round	Conditioning Temperature (°C)	Axial IWTC Location(s) WRT RFT (mm)	Experimental Probe Depths (mm)	Calculation Probe Depths (mm)
DM13	21	457	1.52	1.016, 1.27, 1.52
M865	21	640	1.27	1.27, 1.52, 1.78
		1,050	1.27	1.27, 1.52, 1.78
		1,350	1.27	1.27, 1.52, 1.78
		1,600	1.27	1.27, 1.52, 1.78
M829	21	640	1.27	1.52, 1.78, 2.032
		1,050	1.27	1.016, 1.27, 1.52
		1,350	1.27	1.27, 1.52, 1.78
		1,600	1.27	1.016, 1.27, 1.52
M829	49	640	1.27	1.52, 1.78, 2.032
		1,050	1.27	1.016, 1.27, 1.52
		1,350	1.27	1.52, 1.78, 2.032
		1,600	1.27	1.52, 1.78, 2.032

For all plots, three simulated curves differing by depth increments of 0.254 mm (0.01 in) are superimposed over each experimental curve for the specified axial location. Thus, the experimental curve, with assumed probe depth, say, of 1.27 mm (0.05 in), is bracketed by simulated curves of lesser and/or greater presumed depths. In addition, we have simulated the initial barrel temperature to match the initial measured barrel temperature at the circumferential and axial location of the round identified in the experimental curve on each plot, in every figure.

4.1 DM13 Round (21° C). Figure 8 displays simulated curves corresponding to probe depths of 1.016, 1.27, and 1.52 mm (0.04, 0.05, and 0.06 in). Also superimposed on this plot is the experimental curve corresponding to an assumed depth of 1.524 mm (0.06 in).

Several features of this plot are noteworthy and these relate to:

- apparent noise of experimental curve (corresponding to welded IWTC), and
- relatively poor agreement with magnitude and trends of simulated curves

Noise in this experimental curve is believed due to the large distance between the IWTC probe and the amplifier. Moreover, possibilities also exist for extraneously induced currents caused by "ground loop" from wet lines as well as "line whipping" during gun recoil.

It should be noted that, in this comparison, the IWTC probe is located in the chamber region of the barrel, where, presumably, the combustible cartridge case partially insulates the surface from direct exposure to the propellant gases until the case has been consumed. The effect of the randomly breaking/burning cartridge case has not been incorporated into XBR2D-V29, as yet. Thus, it is not surprising that theory and experiment are not in agreement in the chamber region, even if the probe depth is, indeed, 1.52 mm.

4.2 M865 Round (21° C). Figure 9 displays four plots for the M865 round, conditioned to 21° C at axial probe locations of 640, 1,050, 1,350, and 1,600 mm (25.2, 41.3, 53.1, and 63.0 in). The simulated curves represent depths of 1.27, 1.52, and 1.78 mm (0.05, 0.06, and 0.07 in). It is apparent that these curves generally bracket the superimposed experimental curve, drilled to an assumed depth of 1.27 mm (0.05 in). Discrepancies between the experimental and simulated curves are compatible with presumed error in the drilled probe depth, and round-to-round variation in the experimental temperature profile.

4.3 M829 Round (21° C). Figure 10 displays four plots for the M829 round, conditioned at 21° C at axial probe locations of 640, 1,050, 1,350, and 1,600 mm (25.2, 41.3, 53.1, and 63.0 in). It is noteworthy that horizontal (time) translation of all simulated curves by approximately 40 ms would seem to yield excellent correspondence between experimental and simulated curves in most cases. Though some of this temporal disparity may be due to an overly simplistic model of the ignition delay and flamespreading process, it is believed that the majority of time difference is due to uncertainty in the experimental ignition fiduciary.

From Figure 10a, the differences in shape and magnitude of the simulated temperature-vs.-time plots from a probe depth of 1.52 mm to a probe depth of 2.03 mm are nearly identical to the range of shape

and magnitude differences found for the M829 rounds in Figures 6a–c. This provides, as promised, the evidence that circumferential temperature discrepancies are most likely due to circumferential variation in the probe depths.

Finally, we can see that the M829 rounds in Figure 10 produce a greater barrel temperature rise than the M865 round in Figure 9, at all axial locations. This experimental result is consistent with the ordering of the simulated bore surface temperatures in Figure 5.

4.4 <u>M829 Round (49° C)</u>. Figure 11 is a set of plots which are counterparts to Figure 10 (i.e., same type of round, but at higher conditioning temperature). Similar behavior is observed between the two figures, although the required temporal translation of the time axis is not as great for the 49° C plots as for the 21° C plots.

We note that even though the simulated bore surface temperatures are higher for the higher preconditioned round temperature, we do not detect a noticeable difference in the IWTC measurements between an M829 at 21° C and an M829 at 49° C. It is suspected that the effect of preconditioning is masked by the inherent round-to-round variation in barrel heat input and the small sample size tested.

Overall, the experimental temperature histories, in conjunction with the simulations in Figures 9–11 corroborate each other, wherever two or more plots reference the same probe, with regard to indicating the probable IWTC depth. The examples are as follows: Figures 9a and 11a, and, to a lesser extent, Figure 10a, indicate that the IWTC at 640 mm and 240° (eight o'clock) from RFT is between 1.52 and 1.78 mm below the bore surface. Likewise, Figures 9c and 10c indicate the same depth for the probe at 1,350 mm and 0° (top) from RFT. Furthermore, Figures 9d and 11d point to the same depth for the probe at 1,600 mm and 0° from RFT. Lastly, Figures 9–11 consistently show that the probe temperature at 1,050 mm and 240° is higher than any other location. But, rather than conclude that the firing heat input is simply higher at this location, Figures 9b, 10b, and 11b all suggest that it is higher than elsewhere because the probe is closer here than elsewhere—probably lying between 1.02 mm and 1.27 mm below the surface.

5. SUMMARY

The XBR2D-V29 heat transfer/conduction code, as revised by the U.S. Army Research Laboratory (ARL), has been used in conjunction with the XKTC interior ballistic code to provide barrel temperature predictions for the M256 120-mm cannon firing various ammunition. We found that the predicted bore surface temperature is consistent with that reported elsewhere (using a different numerical procedure). We have also shown experimental barrel temperature data taken from IWTC near the barrel's inner wall. The predictions agree reasonably well with the experimental results. For the most part, discrepancies between the experimental and simulated curves are compatible with the presumed error in the drilled probe depth, and round-to-round variation in the experimental temperature profile. Nevertheless, areas where helpful modifications might be made would include: (1) a modeling option for combustible cartridge case effects in the XBR2D-V29 code, and (2) a refinement of the timing involved in the ignition delay and flame spreading process in the XKTC code. Work in the latter area is ongoing at ARL.

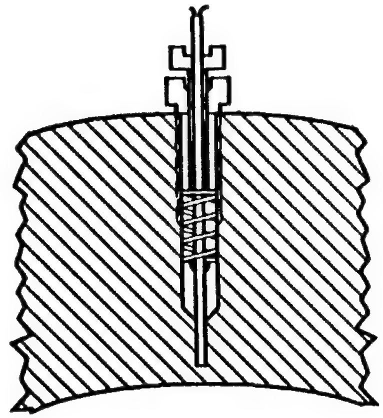


Figure 1. Typical Veritay IWTC installation.

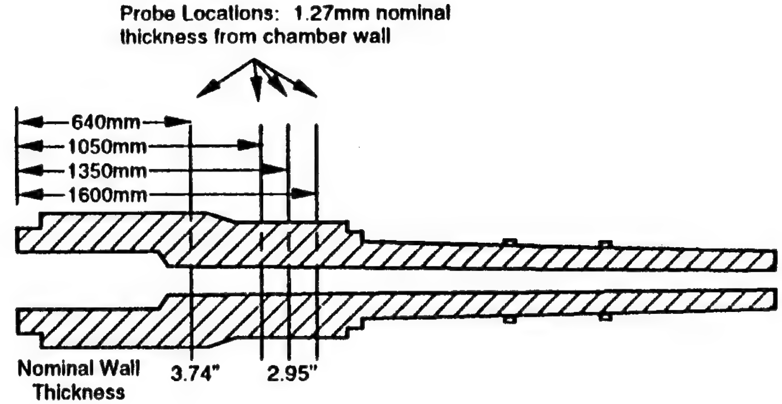


Figure 2. October 1993 modifications to M256 120-mm gun, serial no. 91.

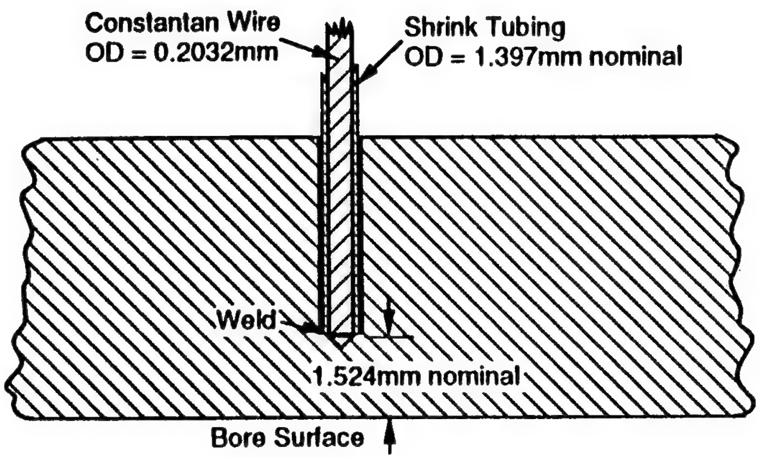


Figure 3. Typical welded IWTC installation.

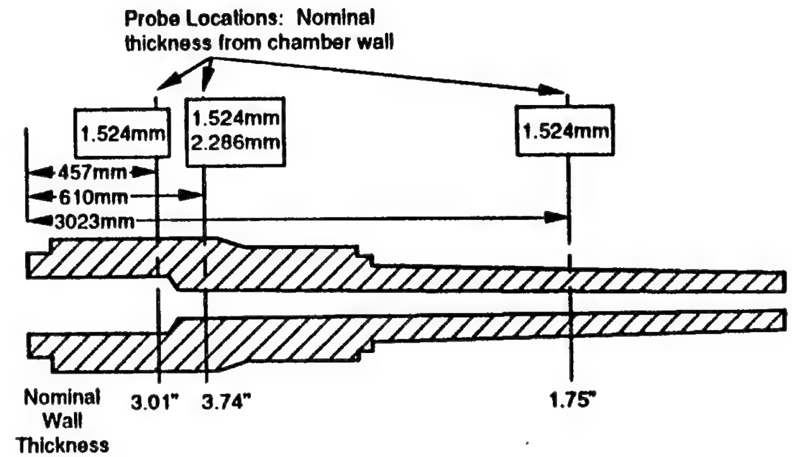


Figure 4. August 1994 modifications to M256 120-mm gun, serial no. 1910.

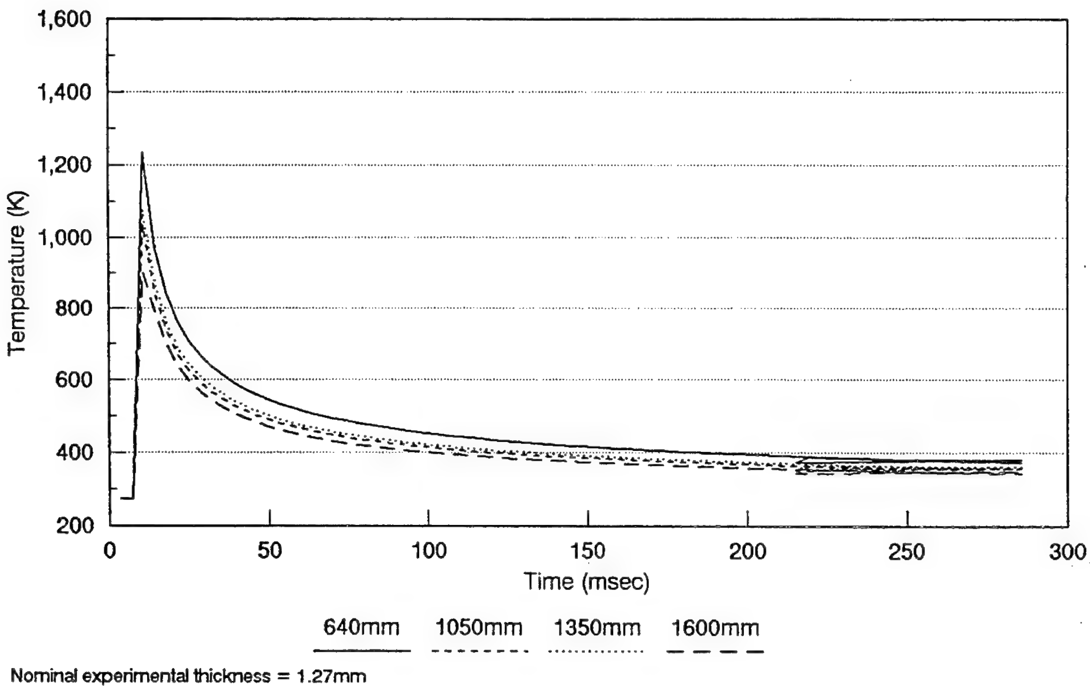


Figure 5a. Simulated bore surface temperatures for M865 (21° C).

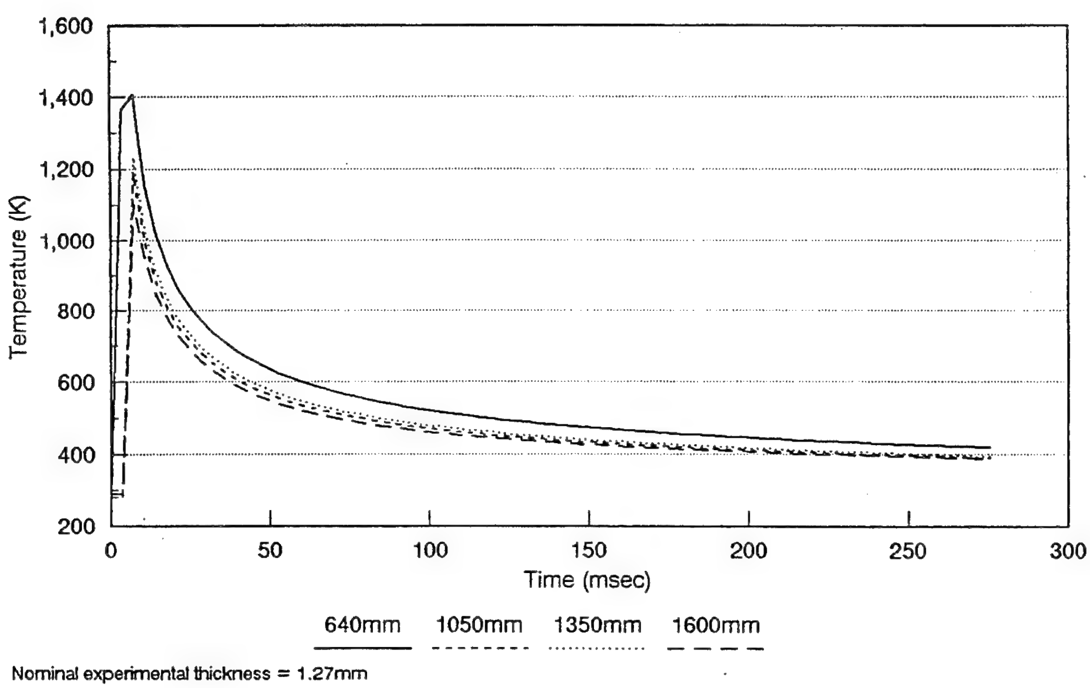


Figure 5b. Simulated bore surface temperatures for M829 (21° C).

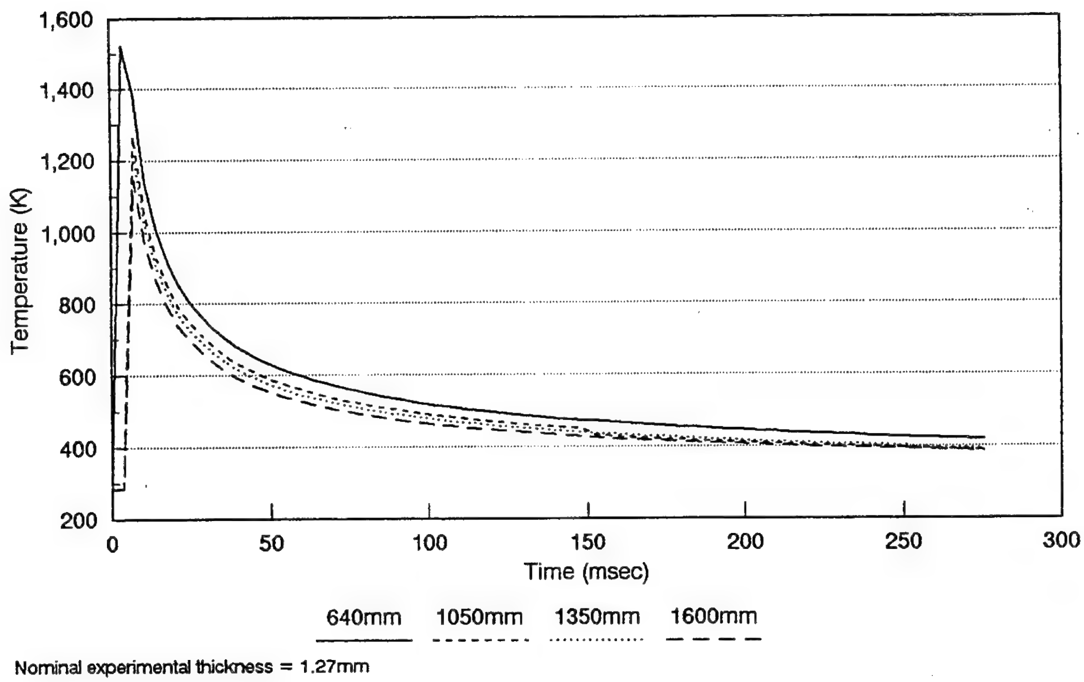


Figure 5c. Simulated bore surface temperatures for M829 (49° C).

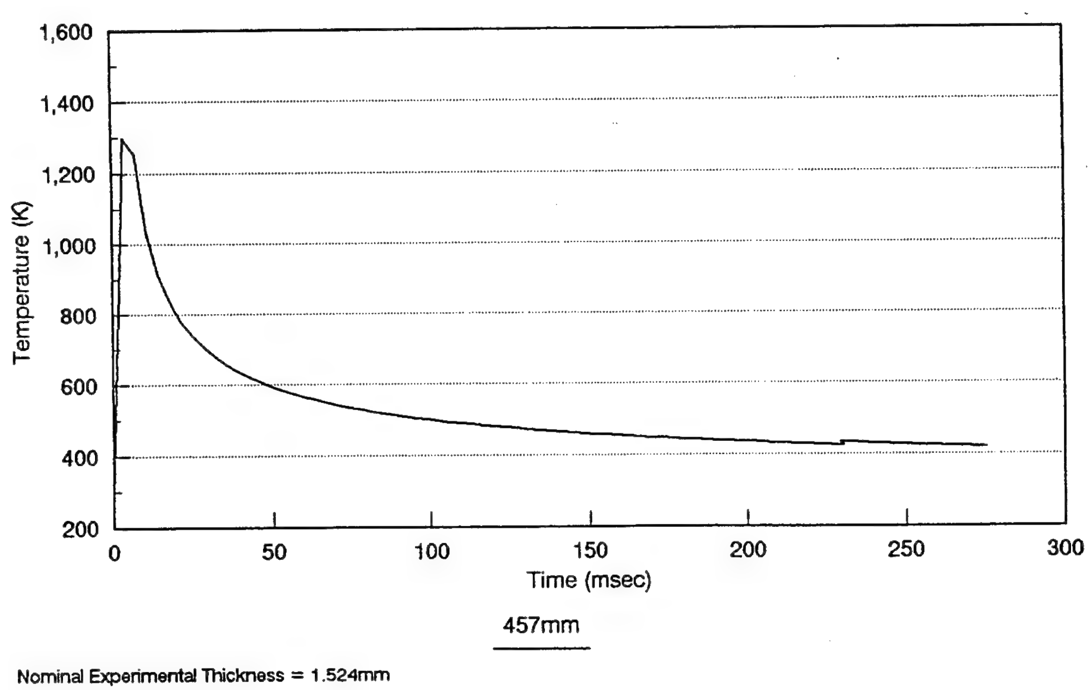


Figure 5d. Simulated bore surface temperatures for DM13 (21° C).

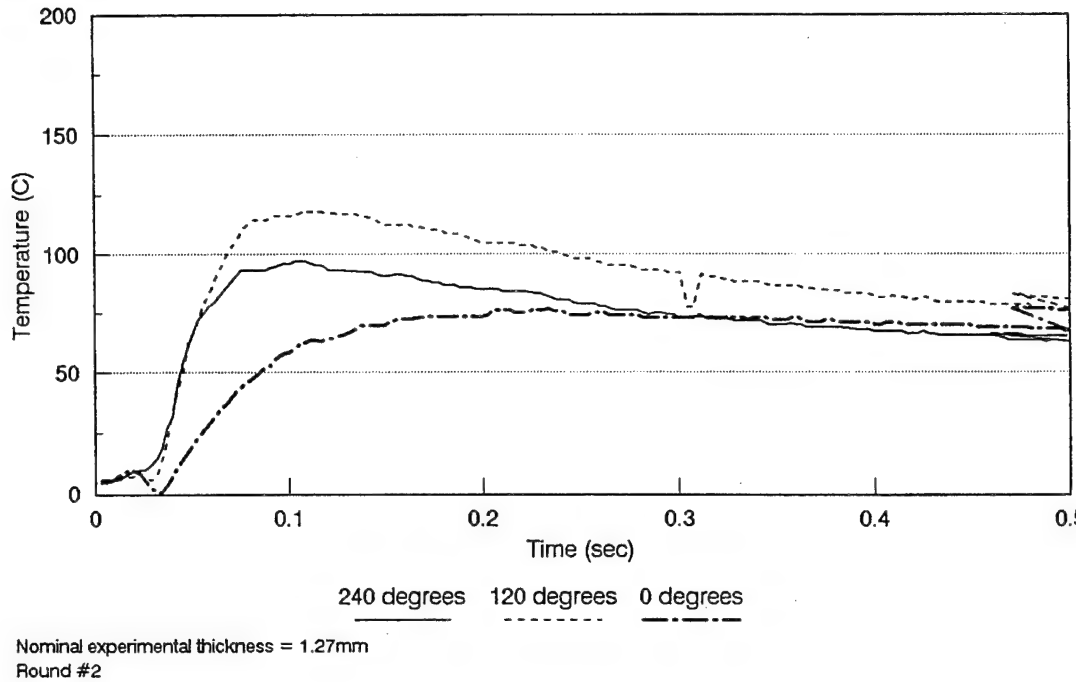


Figure 6a. M829 experimental probe temperatures at 21° C for circumferential positions at 640 mm from RFT—round no. 2.

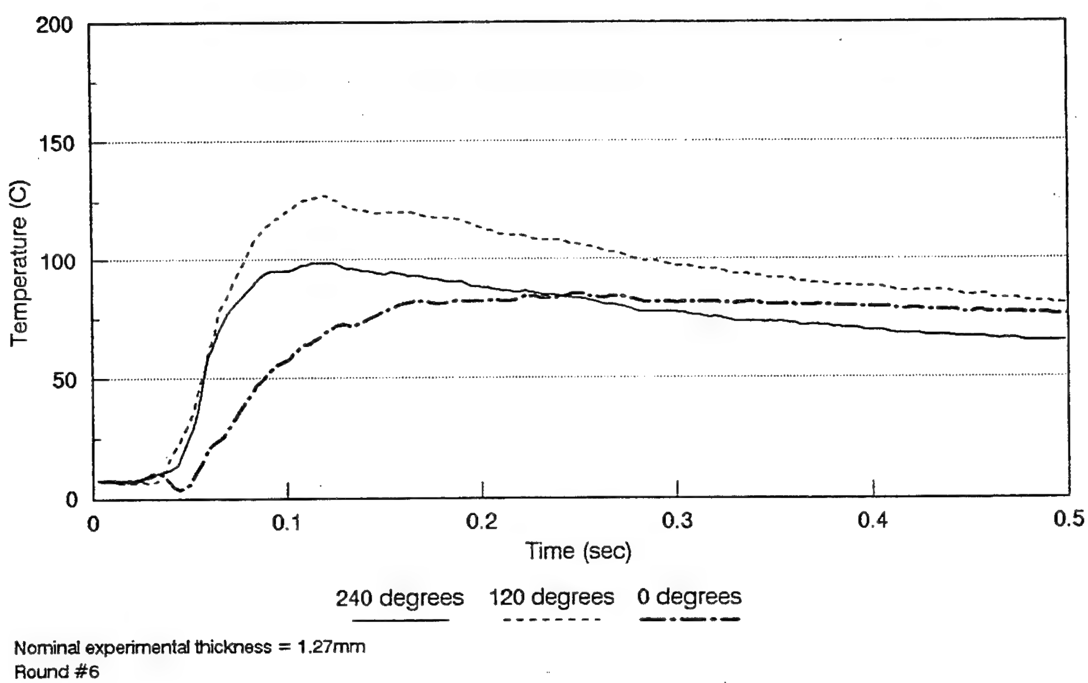


Figure 6b. M829 experimental probe temperatures at 21° C for circumferential positions at 640 mm from RFT—round no. 6.

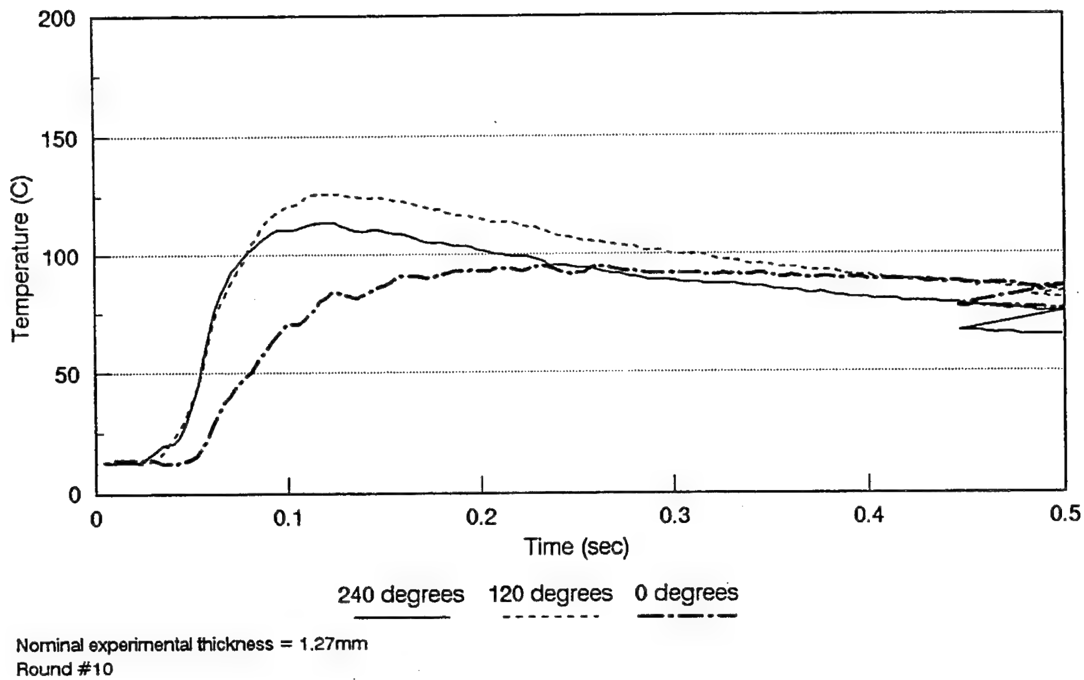


Figure 6c. M829 experimental probe temperatures at 21° C for circumferential positions at 640 mm from RFT—round no. 10.

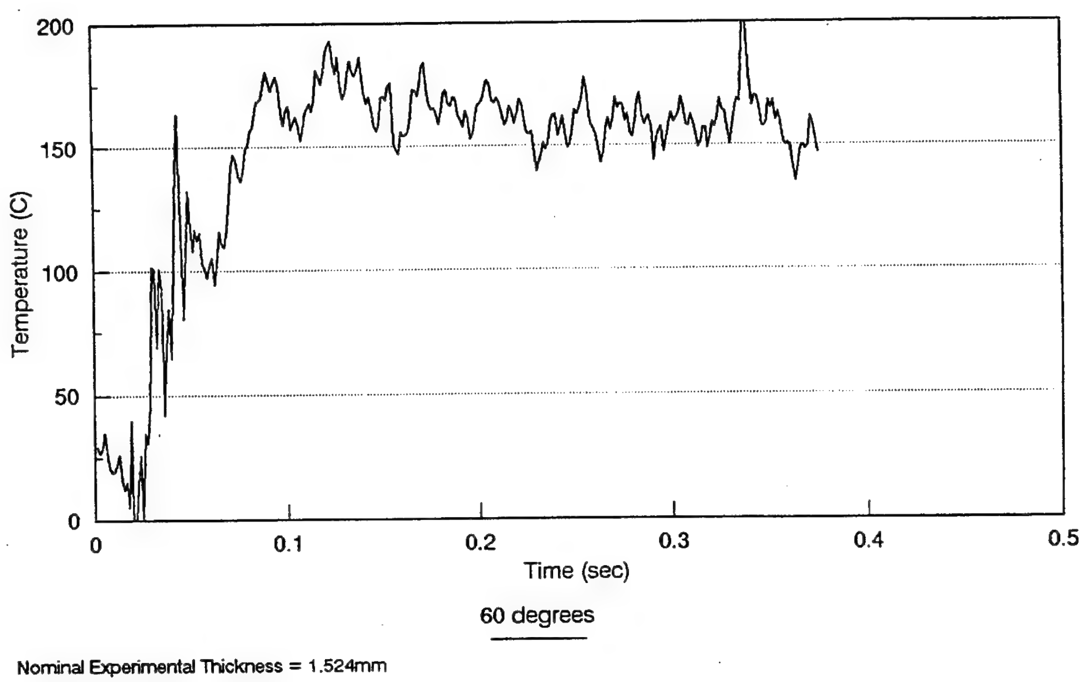


Figure 6d. DM13 experimental probe temperature at 21° C at 457 mm from RFT.

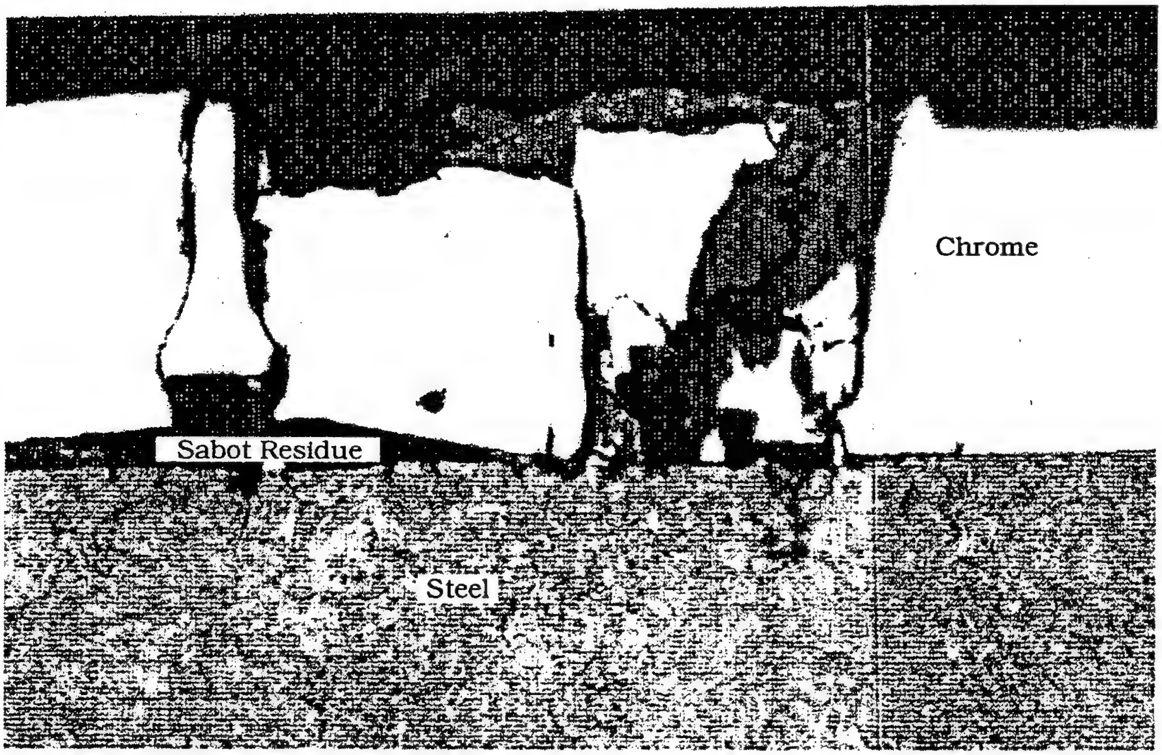


Figure 7. Photomicrograph of chrome-steel interface showing debonding voids filled by sabot material residue (courtesy of Joe Cox, Benet Laboratory).

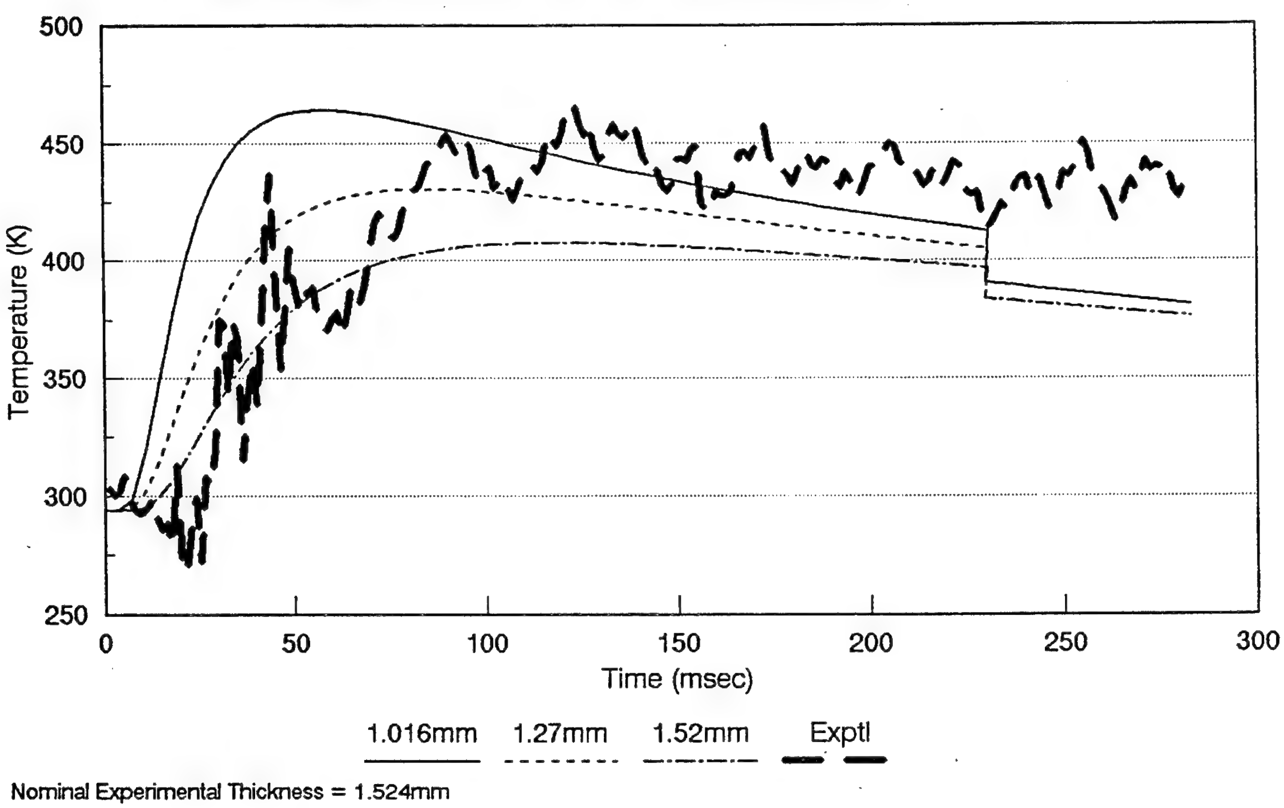


Figure 8. DM13 simulated and experimental probe temperatures at 21° C.

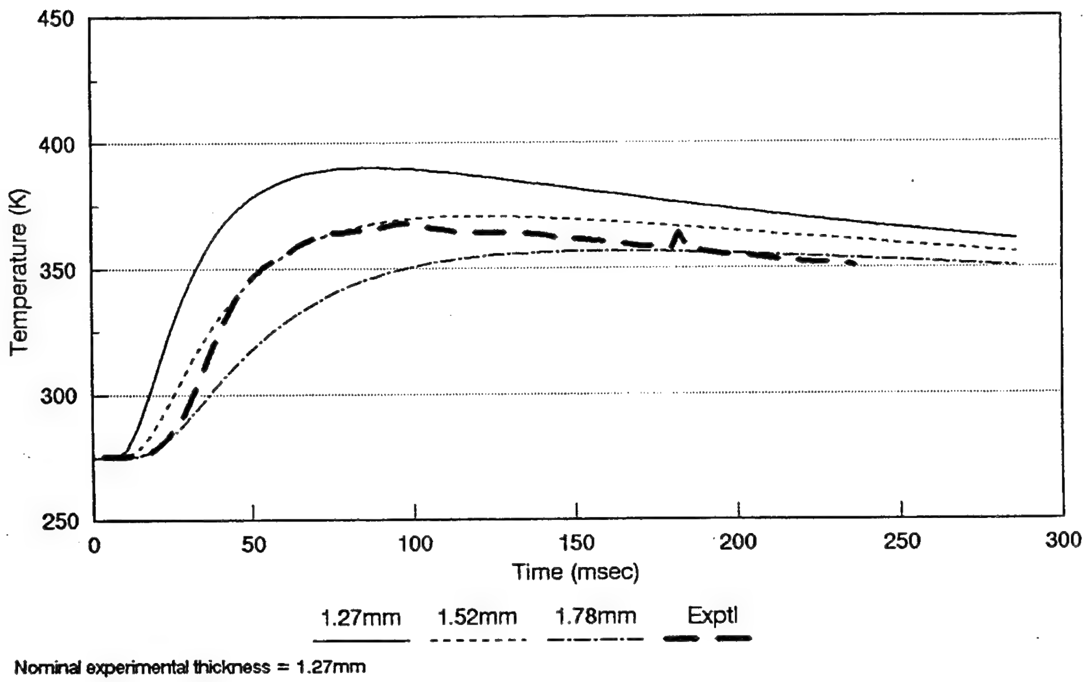


Figure 9a. M865 simulated and experimental probe temperatures at 640 mm from RFT at 21° C—round no. W2/240.

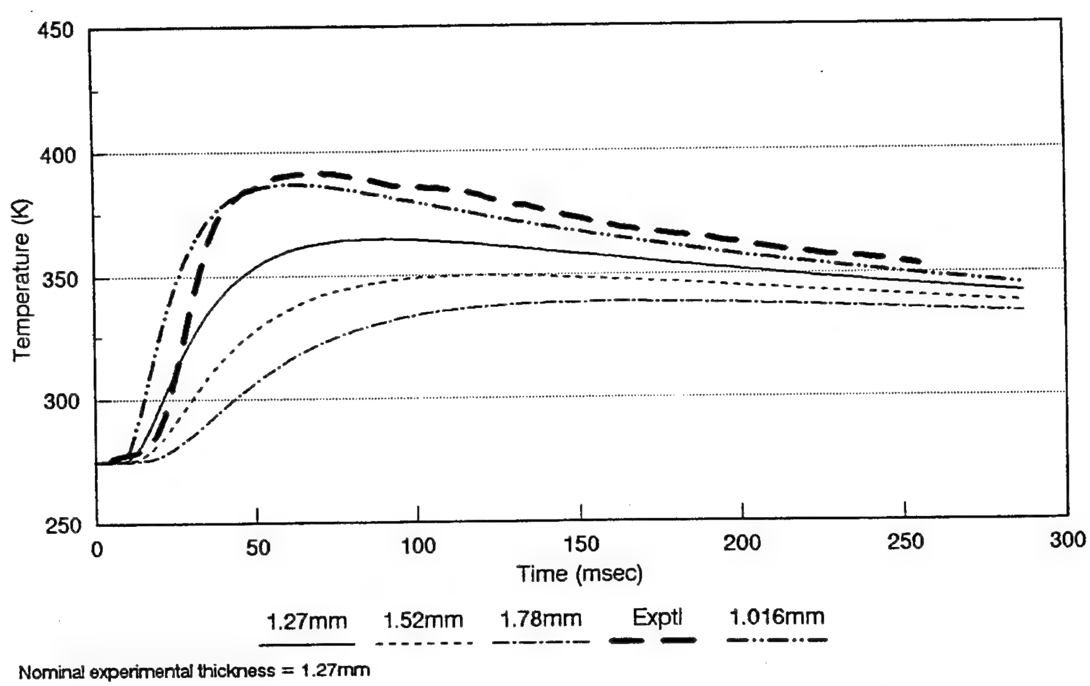


Figure 9b. M865 simulated and experimental probe temperatures at 1,050 mm from RFT at 21° C—round no. W2/120.

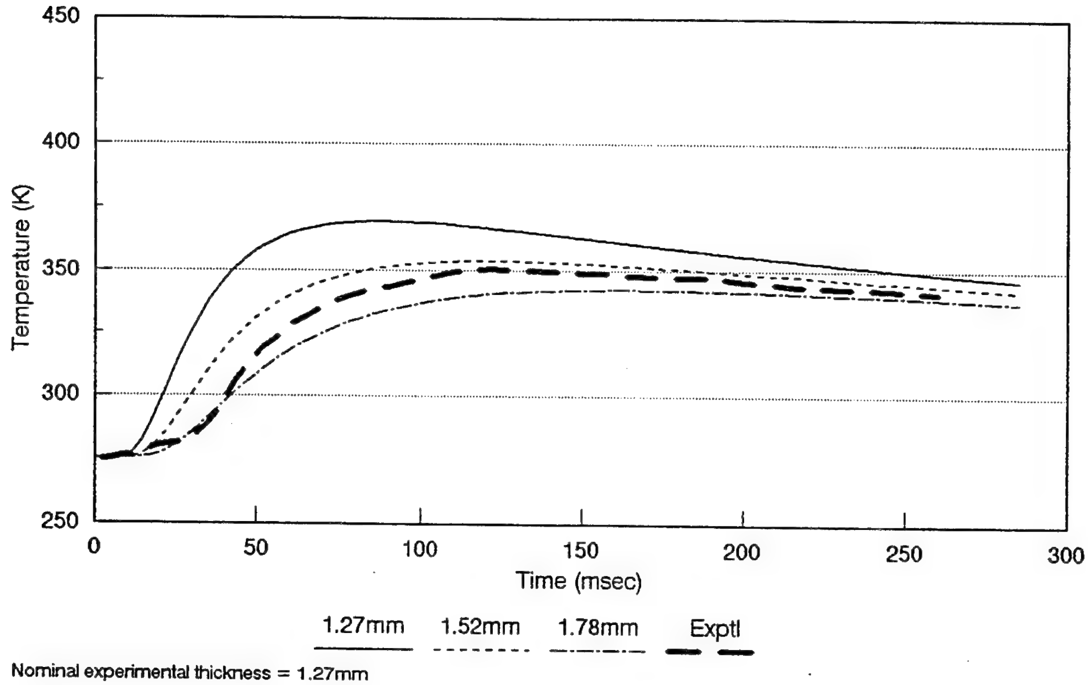


Figure 9c. M865 simulated and experimental probe temperatures at 1,350 mm from RFT at 21° C—round no. W2/0.

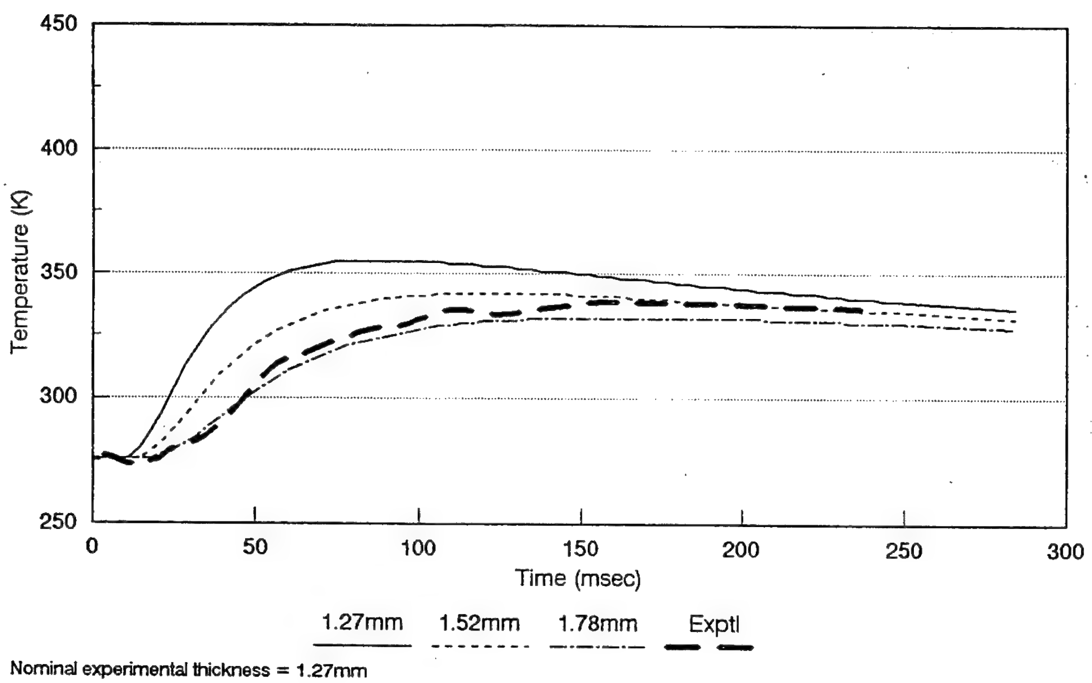


Figure 9d. M865 simulated and experimental probe temperatures at 1,600 mm from RFT at 21° C—round no. W2/0.

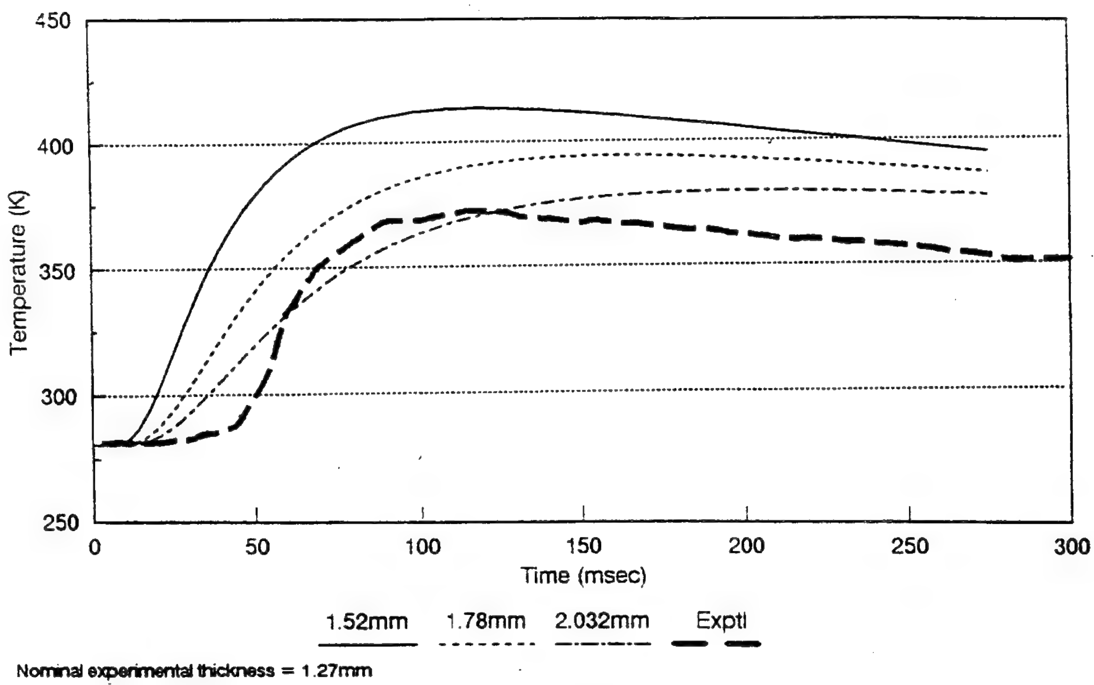


Figure 10a. M829 simulated and experimental probe temperatures at 640 mm from RFT at 21° C—round no. 6/240.

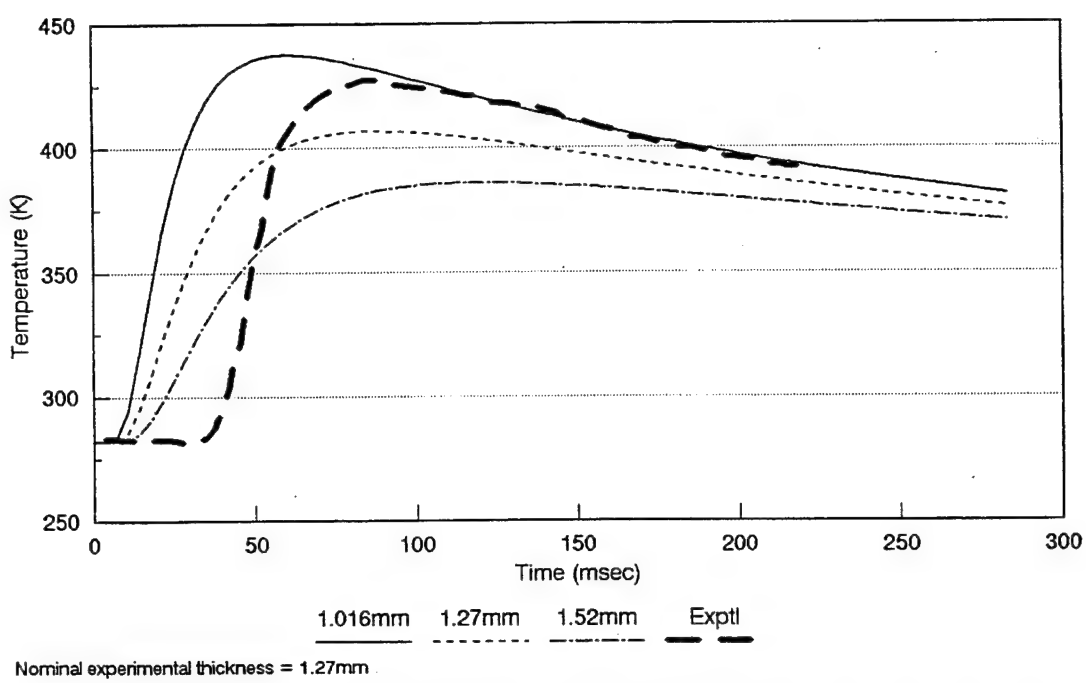
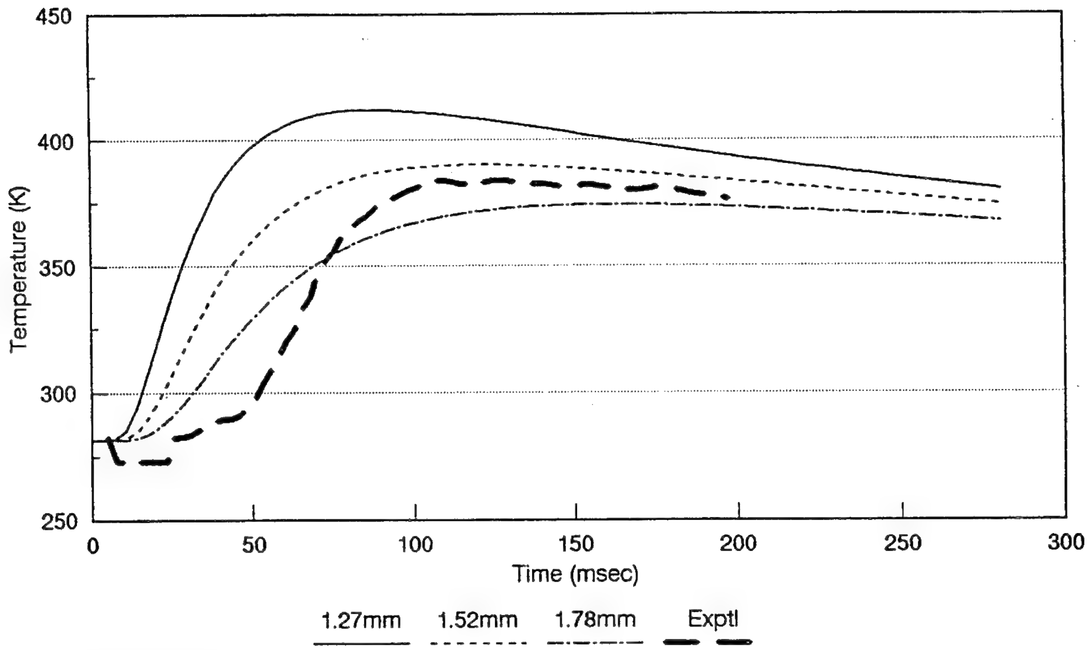
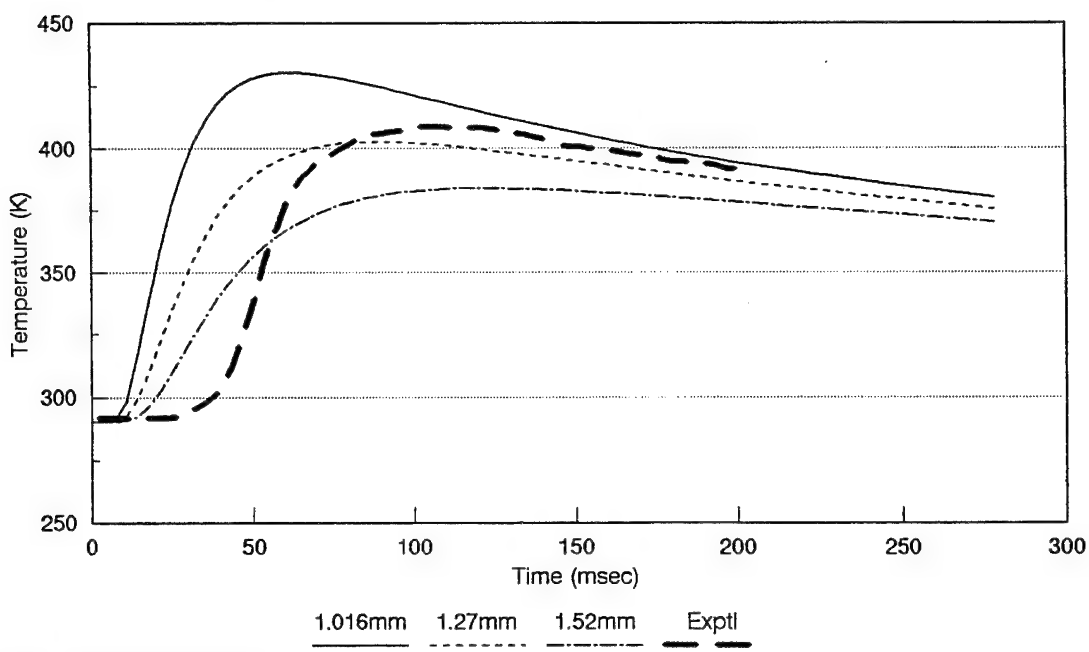


Figure 10b. M829 simulated and experimental probe temperatures at 1,050 mm from RFT at 21° C—round no. 6/120.



Nominal experimental thickness = 1.27mm

Figure 10c. M829 simulated and experimental probe temperatures at 1,350 mm from RFT at 21° C—round no. 6/0.



Nominal experimental thickness = 1.27mm

Figure 10d. M829 simulated and experimental probe temperatures at 1,600 mm from RFT at 21° C—round no. 10/240.

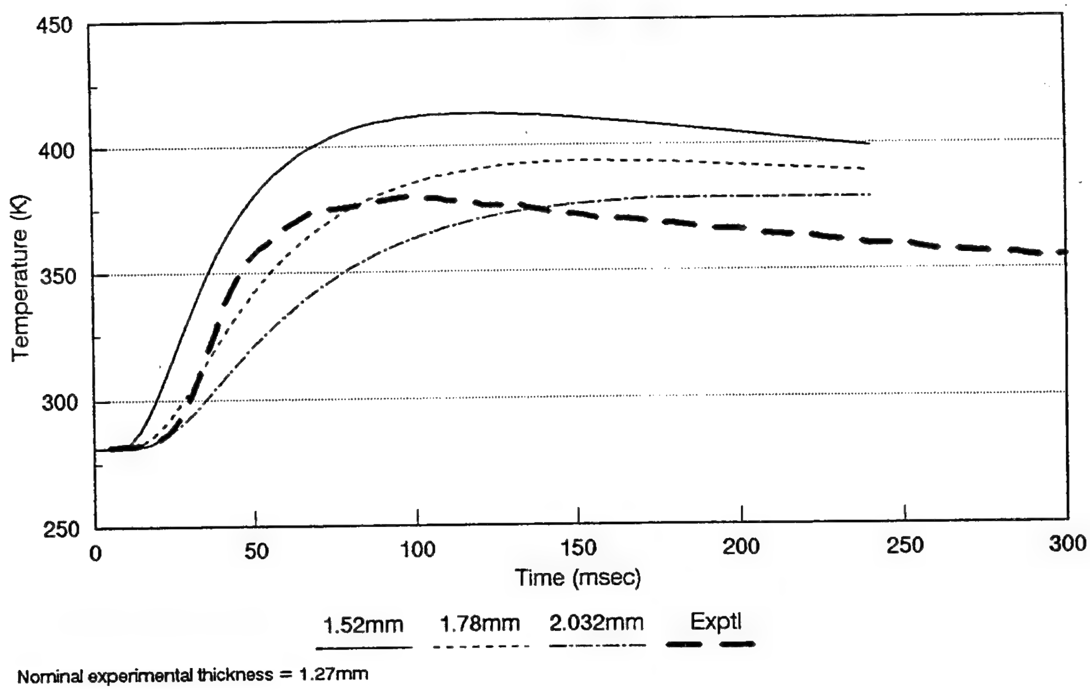


Figure 11a. M829 simulated and experimental probe temperatures at 49° C at 640 mm from RFT—round no. 4/240.

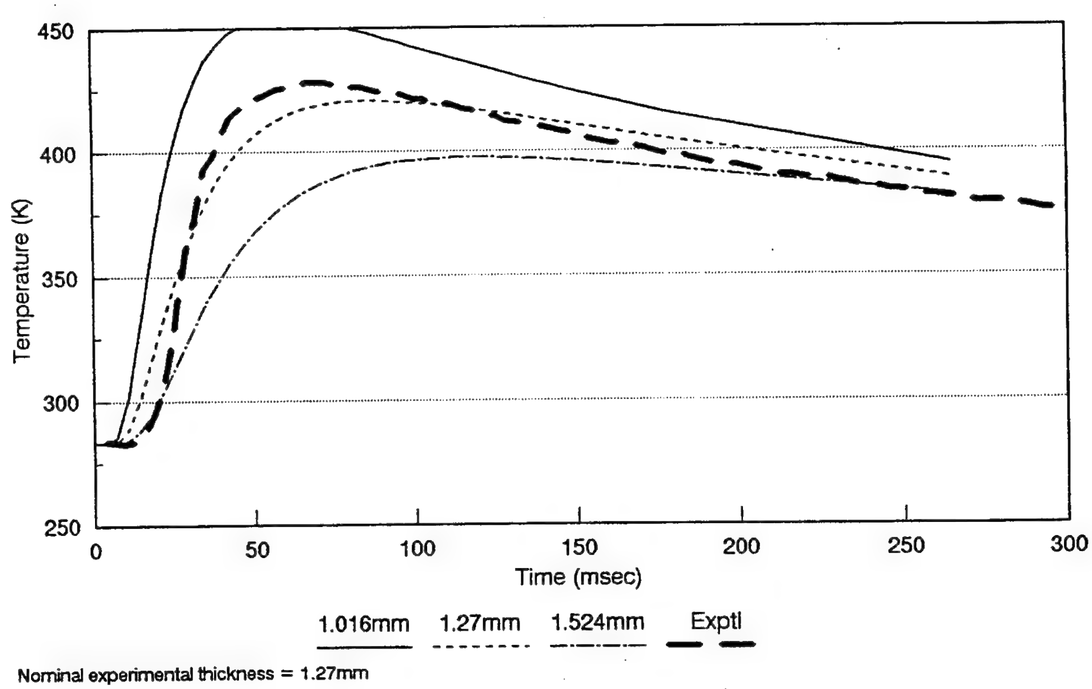


Figure 11b. M829 simulated and experimental probe temperatures at 49° C at 1,050 mm from RFT—round no. 4/120.

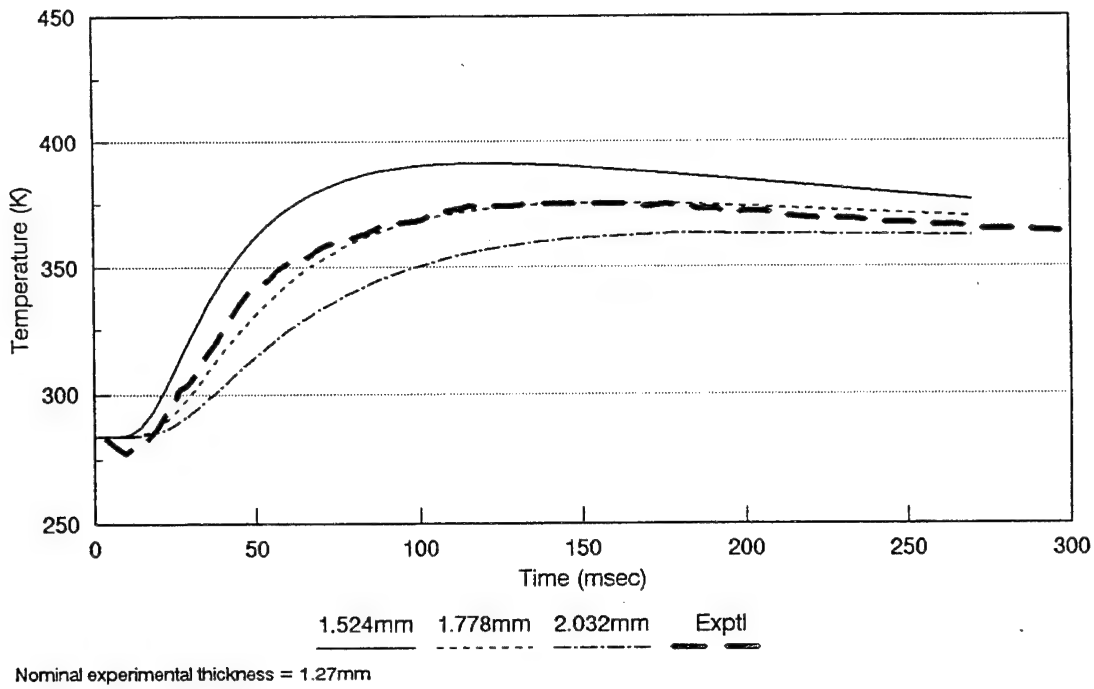


Figure 11c. M829 simulated and experimental probe temperatures at 49° C at 1,350 mm from RFT—round no. 4/240.

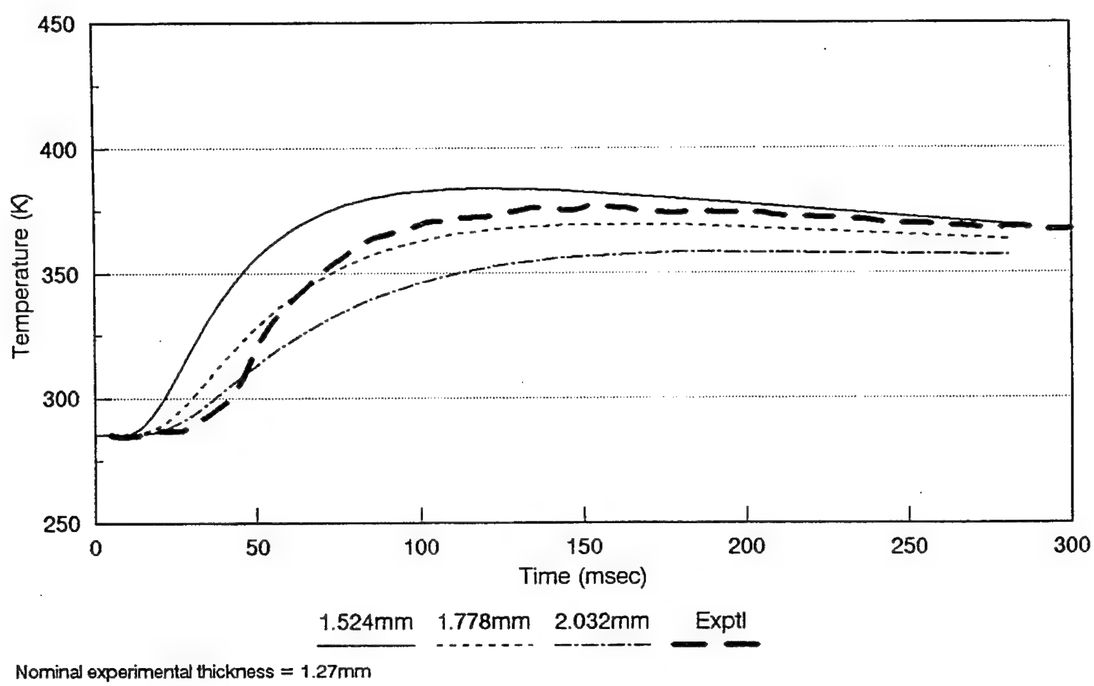


Figure 11d. M829 simulated and experimental probe temperatures at 49° C at 1,600 mm from RFT—round no. 4/0.

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